# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
01/31/2018

**2. REPORT TYPE**
Final

**3. DATES COVERED** *(From - To)*
7/15/16-10/31/17

**4. TITLE AND SUBTITLE**
Instrumentation for Linear and Nonlinear Optical Device Characterization

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
N00014-16-1-2544

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
J. T. Gopinath, V. M.Bright and W. Park

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
REGENTS OF THE UNIVERSITY OF COLORADO
UNIVERSITY OF COLORADO
3100 MARINE ST., RM 279 572 UCB
BOULDER CO 80303-1058

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
ONR, Mike Wardlaw, MIKE.WARDLAW@NAVY.MIL
ONR OCEAN SENSING & SYSTEMS APPS DIV
875 N. Randolph Street
Arlington VA 22203-1995

**10. SPONSOR/MONITOR'S ACRONYM(S)**

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for Public Release, distribution is Unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The PI has acquired six pieces of equipment to extend capabilities for linear and nonlinear device characterization. The requested equipment spans a large wavelength range and and will provide new resources for spatial, temporal and frequency domain studies and control. The new measurements will complement existing equipment for photonic and nanostructures studies already in the PIs lab such as a spectrometer, visible and near infrared lasers, modulators, and waveguide characterization equipment. The access to both higher speed measurements, phase control, and new spectral regions will enable powerful materials and device characterization.

**15. SUBJECT TERMS**
laser, wavemeter, oscilloscope, spatial light modulator, lock-in amplifier

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)* |
|---|---|---|---|---|---|
| U | U | U | UU | 4 | Juliet Gopinath / 303 492 5568 |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

## INSTRUCTIONS FOR COMPLETING SF 298

**1. REPORT DATE.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

**2. REPORT TYPE.** State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

**3. DATE COVERED.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

**4. TITLE.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

**5a. CONTRACT NUMBER.** Enter all contract numbers as they appear in the report, e.g. F33315-86-C-5169.

**5b. GRANT NUMBER.** Enter all grant numbers as they appear in the report. e.g. AFOSR-82-1234.

**5c. PROGRAM ELEMENT NUMBER.** Enter all program element numbers as they appear in the report, e.g. 61101A.

**5e. TASK NUMBER.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

**5f. WORK UNIT NUMBER.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

**6. AUTHOR(S).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES).** Self-explanatory.

**8. PERFORMING ORGANIZATION REPORT NUMBER.** Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

**10. SPONSOR/MONITOR'S ACRONYM(S).** Enter, if available, e.g. BRL, ARDEC, NADC.

**11. SPONSOR/MONITOR'S REPORT NUMBER(S).** Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

**12. DISTRIBUTION/AVAILABILITY STATEMENT.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

**13. SUPPLEMENTARY NOTES.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

**14. ABSTRACT.** A brief (approximately 200 words) factual summary of the most significant information.

**15. SUBJECT TERMS.** Key words or phrases identifying major concepts in the report.

**16. SECURITY CLASSIFICATION.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

**17. LIMITATION OF ABSTRACT.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

# DURIP Final Report: Instrumentation for Linear and Nonlinear Optical Device Characterization

J. T. Gopinath, V. M. Bright and W. Park

January 29, 2018

**Major goals and objectives of the project** The PIs acquired equipment to extend capabilities for linear and nonlinear optical device characterization. The requested equipment spans a large wavelength range and will provide new resources for spatial, temporal and frequency domain studies and control. The new measurements will complement existing equipment for photonic and nanostructures studies already in the PIs lab such as a spectrometer, visible and near infrared lasers, modulators, and waveguide characterization equipment. The access to both higher speed measurements, phase control, and new spectral regions will enable powerful materials and device characterization, allowing to continue state-of-the-art research.

The proposed equipment addresses several important research goals of DoD programs including:

- Nanoscale material characterization
- Non-mechanical beam steering and focusing
- Optical spectroscopy of materials and devices
- Testing of optical components and devices
- High resolution optical spectral analysis
- Frequency comb generation in mid-infrared

**Accomplishments** Six major pieces of equipment have been ordered and received:

1. Real time oscilloscope (Tektronix) [Figures 1]
2. Mid-infrared camera (FLIR systems) [Figure 2-3]
3. Stanford Research Systems (Lock-in amplifier) [Fig 4]
4. Wavemeter (Bristol) [Fig 5]
5. Single frequency mid-infrared laser system (Argos, Lockheed Martin) [Fig 5]
6. Spatial light modulator (Meadowlark) [Fig 6]

The oscilloscope, mid-infrared camera, spatial light modulator, and lock-in amplifier have been fully integrated into experimental set up and are generating valuable research results. The Argos laser has been installed in the lab and training of personnel has occurred (May 2017). Examples of current results follow.

1. <u>Mid infrared synchronously pumped optical parametric oscillator</u> We have constructed a mid-infrared synchronously pumped optical parametric oscillator utilizing the mid-infrared camera and the real time oscilloscope purchased under this program (Figures 1 and 2). The goal was to construct an OPO to produce tunable 1.5 – 1.8 and 3- 4 micron light for spectroscopy. The OPO has been constructed, characterized and is being used for pump-probe spectroscopy. Using a 2.1 W, 230 fs, 1040 nm pump, we generated 200 mW of 140 fs, 2.9-4.2 um idler light at a repetition rate of 77 MHz. Our low OPO threshold (0.15 W) is achieved by tight focusing in the PPLN crystal, where both our pump and signal have a waist of 12 um.

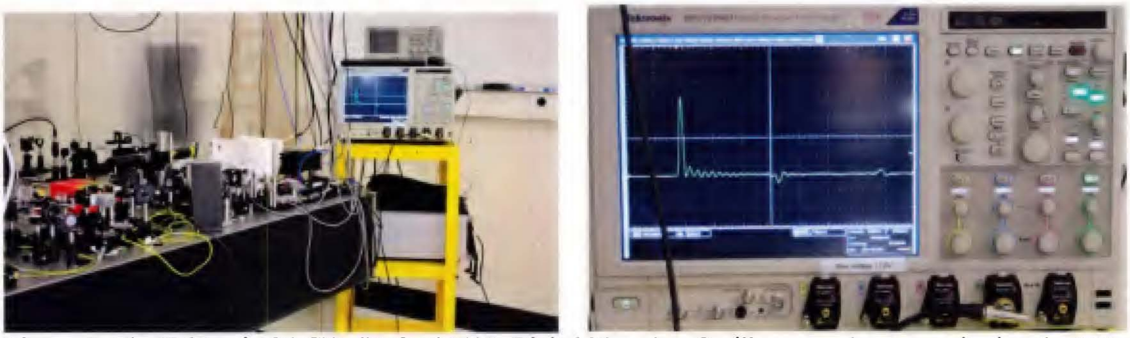


**Figure 1.** The Tektronix 25 GHz DPO 72540D Digital Phosphor Oscilloscope, shown monitoring the 300 ps time lens laser system. In the future, we plan to shorten the pulses coming from the seed laser to reduce satellite peaks through the amplifiers. We are going to switch to using a 50 ps electronic pulse generator to gain-switch the seed diode, and the 25 GHz scope is the only device in the lab with the bandwidth to characterize these signals. The oscilloscope was also used to characterize the long-term stability of a lab-built synchronously pumped optical parametric oscillator (OPO). With its long record length (10 megasamples), kHz variations were measurable even over an hour of monitoring. These results were instrumental in improving the OPO stability by a factor of 2.5.

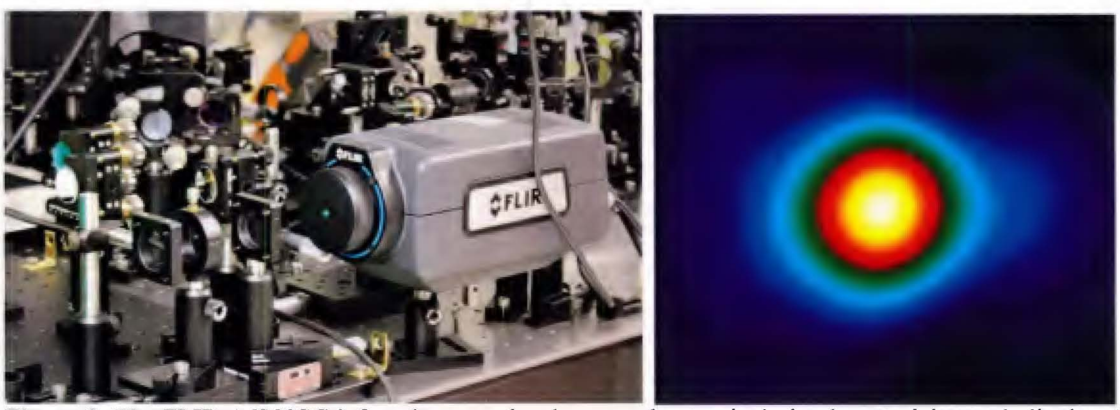
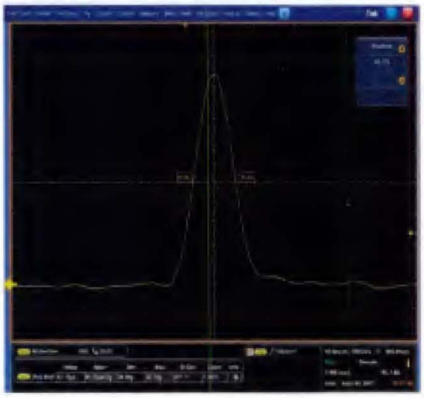



**Figure 2.** The FLIR A6700SC infrared camera has been used extensively in characterizing and aligning the mid-infrared output of a lab-built optical parametric oscillator (OPO). It has been used to improve the beam quality of this system, critical for accurate measurements of the nonlinear coefficient of our bulk chalcogenide glasses. The fast response of the camera has also been necessary for aligning the mid-infrared OPO idler light through our pump-probe spectroscopy system. Here it is shown (shutter closed) set up to monitor the output idler beam quality of the OPO. This camera was used to take the image of the idler beam profile shown in the right hand side of the figure.

2. Short pulse laser characterization We are studying a short pulse diode laser system at 976 nm for multiphoton imaging. The Tektronix 25 GHz Digital Phosphor Oscilloscope has been used to characterize an electronic pulse generator with a pulse width of < 50ps and the optical pulses from a gain-switched diode laser, currently hundreds of picoseconds. Figure 3 illustrates example data taken from the oscilloscope.



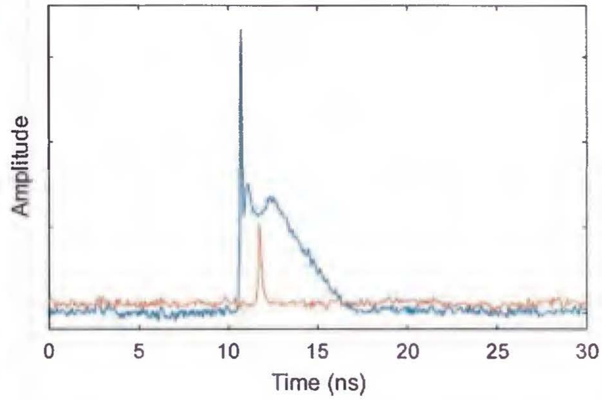



**Figure 3.** (a) A screen shot from the oscilloscope with a signal from an electronic pulse generator. The scope has been used to characterize pulses with widths less than 50 ps (42 ps FWHM shown here). (b) Pulses from the 976 nm seed laser characterized using the Lab Buddy detector and the oscilloscope. The optical pulses coming from the seed laser are currently hundreds of ps long. In the future further research is required to generate pulses from the seed laser that optimize the output from the time lens laser. The scope will be useful in making these determinations and improving the laser design.

3. Capacitive sensors The SR830 lock-in amplifier has been used for exploratory sensor research. For instance, one project is developing capacitive sensors from structures less than 50 nm thick, formed by atomic layer deposition. For detection of any changes in capacitance, high frequency (rather than DC) signal processing is preferred. Tiny capacitance values can be brought to a detectable range at higher frequencies. To recover low-frequency signals applied to a capacitor energized by a high-frequency carrier wave, a demodulator is needed. When the lock-in amplifier uses the carrier wave as a reference, it performs product demodulation of the signal from the capacitor (Figure 4), recovering the signal after transduction by the capacitive sensor.

**Figure 4.** The SR830 lock-in amplifier is integral to performing many of our sensitive, low-level measurements. With its strong noise rejection, it is capable of measuring nanovolts of signal. This has been useful in measuring the transmitted light through our waveguides, allowing operators to optimize signals even starting from significant misalignment. The frequency selective mode of operation has also facilitated work on the rotational diffraction of orbital angular momentum light.

4. <u>Chalcogenide resonators</u> The Bristol 671A-IR infrared wavemeter is a critical piece of equipment for monitoring, characterizing, and optimizing integrated optical ring resonators. The Bristol's high measurement repeatability and sub-picometer resolution in the mid-IR allows us to measure Q factors greater than ten million.

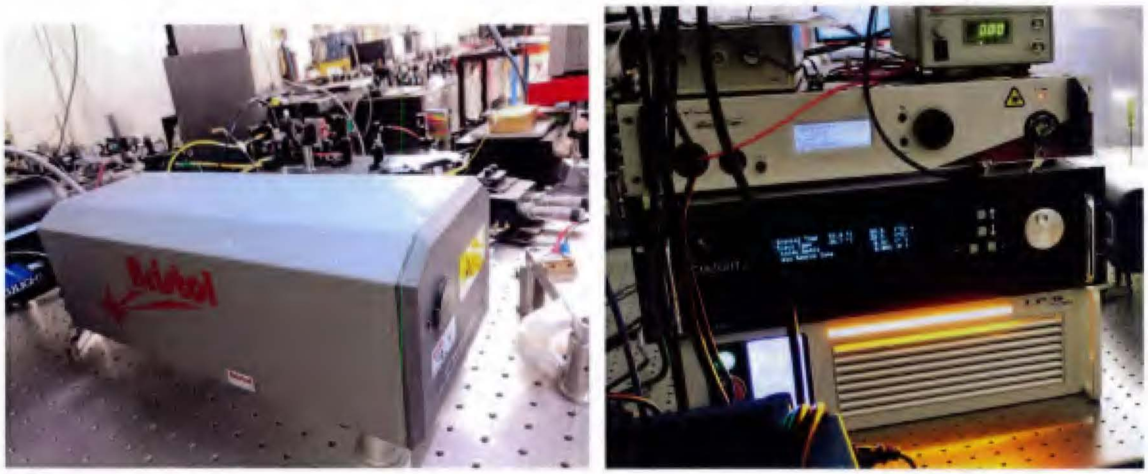


**Figure 5.** Bristol wave meter (left) and Argos optical parametric oscillator (right). The Argos Model 2400 CW OPO Module C has been received, constructed, and evaluated in a lab setting. Personnel have also received direct training from Lockheed-Martin/Aculight for coarse and fine wavelength tuning as well as safety procedures for proper device operation. This system will be used for mid-infrared experiments and also, recently has been used to perform high power characterization of adaptive optical devices.

5. <u>Generation of orbital angular momentum</u> The Meadowlark P1920-0405-0785-HDMI spatial light modulator is a critical piece of equipment for generating orbital angular momentum. It can be used to generate the higher order modes needed for OAM from polarization maintaining fiber and also, to generate OAM directly for sensing. The high efficiency and large numbers of pixels are essential for experiments in this area.

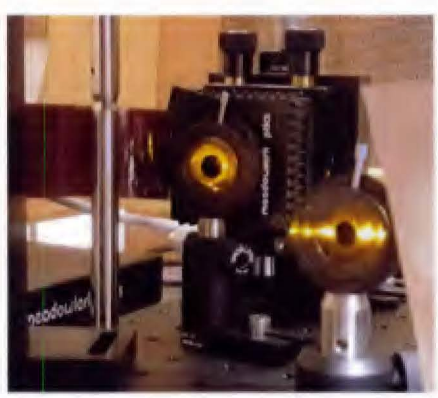


**Figure 6.** Spatial light modulator from Meadowlark, that can operate between 400 to 800 nm. It is reflective with a zero-order diffraction efficiency of 68 to 78% and a response time of 19 ms. The modulator has 1920 x 1152 pixels and is based on a nematic liquid crystal.